



A Study of the Development of a Safety Service Manipulator System with High Dexterity Capability

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論文内容の要旨

Chapter 1 Introduction

Considering a declining birth rates and an aging society which have been serious social problems at present, the request for services requiring physical motions would increase in the near future. Manipulators aimed at providing such physical services to human beings should have both safety and dexterity in order to provide high quality services without damaging human beings. However, most previous manipulator researches have dealt with safety and dexterity issues separately without a consideration of interference between them.

The target of our research is to develop the manipulator system which can achieve high safety and dexterity simultaneously in physical service processes by dealing with them as one not separately. Specifically, the target manipulator system can achieve high velocity, force, and internal failure avoidance ability but its residual impact and pushing forces are suppressed under acceptable criteria. In order to achieve the target, three approaches are taken into account in our research. Firstly, we propose a system aimed at simultaneous achievement of safety and dexterity, which consists of several safety and dexterity measures, secondly, propose control methods for the measures in order to improve the safety and dexterity of the system, and thirdly, propose an index which can evaluate them simultaneously, which might be useful for design and motion planning of the system. As solutions for those approaches, in our research, we propose SSMS(Safety Service Manipulator system), SD torque limit and SD brake, and SD index corresponding to the system, control, and index respectively.

Chapter 2 Safety Service Manipulator system

We proposed SSMS(Safety Service Manipulator system) which is developed for achieving high safety and dexterity in physical service processes. SSMS has four main techniques, BRM(Base Redundant Mechanism), APCS(Air Pressure Collision detection System), CTLB(Controllable Torque limiter in Base), and a base redundancy, to reduce harmful forces and to achieve high velocity, force, and failure avoidance ability.

BRM is a redundant system whose redundancy is constructed by a combination of a movable base and a conventional manipulator. It is a safer mechanism than SRM(Serial Redundant Mechanism), which is a conventional redundant mechanism, on pushing force and impact force because it needs less torque for a motor on its base and has globally low equivalent mass. Its safety on harmful forces was confirmed analytically and

numerically. A base redundancy which is provided by BRM can be utilized in control and motion planning to improve the safety and dexterity.

One of effective methods to reduce impact force generated by colliding between a manipulator and a human is to cover a manipulator with a flexible material and to decrease impact velocity by a brake. In order to realize the both functions, a collision detectable sensor that has flexibility in itself and is able to cover a wide area of a manipulator is required. APCS consisting of a flexible air chamber and a pressure sensor is the sensor that satisfies the requirements. It can detect if collision happens or not by measuring the pressure wave generated by collision with the pressure sensor. Additionally, the flexibility of APCS is effective to reduce impact force, and its space between the upper wall and the lower wall can give enough time for a brake to decelerate impact velocity. Consequently, impact force can be considerably reduced by using APCS when a manipulator crashes to an environment. We made two types of APCS, a tube type and an air-room type which can change detection characteristics by adjusting the stiffness of the air-room, and confirmed the effectiveness in reduction of impact force through impact experiments.

A torque limiter is an effective device to limit motor torque when undesirable contact happens between a manipulator and a human. There are expected various contact situations between them in human environments, thus, it is necessary to install torque limiters to all joints of a manipulator in order to cope with those situations. However, it may causes increasing of weight of links and of integration burden in addition to strong torque restriction in task execution. Installing torque limiters to the base of a manipulator, CTLB, is the one of good solutions to solve the problems. Since CTLB is located on the base of a manipulator, it does not cause weight increasing of links and need to have high transmission torque. Furthermore, they are easily constructed in comparison with ones installed on the joints of arm. When excessive pushing force is applied to a manipulator possessing CTLB, the pushing force is limited by slip of CTLB which causes the slip motion of a manipulator. In that case, pushing force is limited at low level by setting low limit torque for CTLB, therefore, it is desirable for a manipulator to maintain its CTLB to slip as easily as possible. We confirmed that CTLB was effective in reduction of pushing force and in case of low limit torque pushing force was limited at low level through pushing experiments.

We actually integrated all of the above solutions and developed a prototype of SSMs and MiniSSMs. SSMs consists of 5-DOF BRM, eight modules of air-room type APCS, and two CTLBs(controllable clutch), and MiniSSMs consists of 3-DOF BRM, one module of tube-type APCS, and one CTLB(Direct Drive).

Chapter 3 Safe and Dextrous Torque Limit

For SSMs, a slipping motion can be achieved by CTLB, which results in reduction of pushing force. As mentioned in Chapter 2, it is possible to slip faster when external force is applied to a manipulator by setting a lower limit torque value to CTLB. However, the low value of limit torque causes torque limitation, which means the decrease of dexterity on force ability of SSMs in spite of the increase of safety on pushing force. To solve the problem of dexterity decrease, we adopt the method that estimates the torque required for CTLB in a specific task based on the dynamics of SSMs. By setting the estimated torque to CTLB, it is possible that SSMs slips faster in case of unexpected contact but does not slip during task execution. It means that safety on pushing force increases than in case of setting constant limit torque to CTLB without the decrease of dexterity on force ability. We refer to the method as *SD* torque limit. The effectiveness of the *SD* torque limit was confirmed through simulations and experiments.

Chapter 4 Safe and dextrous Brake

The most general brake method is to stop all manipulator joints, zero-brake, which makes naturally the velocity of a contact point be zero. Most researchers adopted the zero-brake for a safety measure to reduce impact force. The zero-brake can be applied to a non-redundant manipulator as well as a redundant manipulator, but its reduction efficiency on impact force is not so high. Moreover, a manipulator braked by the method has possibility to cause undesirable accident due to straying the contact points from an impact direction, which is usually caused by torque saturation. Here, if there is a brake method which can decelerate impact velocity

faster than the zero-brake and keep an impact direction over a brake process. it can achieve higher safety related to impact force and/or higher dexterity related to executive velocity ability than those of the zero brake. In this chapter, Safe and Dextrous brake(*SD* brake) method is proposed, which is an effective brake method that decelerates impact velocity fastly and efficiently. There are two *SD* brakes which are referred to as CNVB(Closest Null space Vector Brake) and DAPB(Dynamic Acceleration Polytope Brake). CNVB uses a closest null space vector from a present velocity configuration to find a optimal deceleration direction in a joint space. DAPB uses a dynamic acceleration polytope that represents the acceleration ability of a manipulator to calculate optimal brake torque. Both methods move a present velocity configuration to the closest null space in a viewpoint of kinematics and dynamics respectively.

Through simulations, it has been confirmed that CNVB could decelerate impact velocity faster than zero-brake without straying from an impact direction on a brake process from the viewpoint of kinematics. However, it did not make sure to keep an impact direction when the maximum deceleration that might cause torque saturation was chosen. Therefore, it is necessary to check if torque saturation occurs or not when it is utilized in a brake. On the other hand, DAPB guaranteed keeping an impact direction on a brake process, moreover, it could decelerate impact velocity faster than zero-brake from the viewpoint of dynamics, which was confirmed by simulations and experiments. In the experiment, we found vibration on a brake process. It could be estimated that the flexibility and backlash in joints were the main reasons of it. Therefore, it is necessary to increase rigidity and to remove backlash to improve the performance of the brake. We confirmed that DAPB could reduce impact force much more than zero-brake through impact experiments. This gives us that by adopting the brake, we can increase execution velocity of a manipulator without increasing an residual impact force.

Chapter 5 *SD* index

In realization of a manipulator possessing safety and dexterity functions together, it is important to make evaluation indices of safety and dexterity. Especially, if it is aimed at realizing the compatibility of both functions, the index representing a correlation between safety and dexterity is indispensable. In this chapter, we propose the *SD* index that is able to evaluate the safety and dexterity of a manipulator simultaneously and quantitatively. The *SD* index is composed of three individual indices, *S* degree, *D* degree, and *SD* degree, which represent safety, dexterity, and the dexterity under safety satisfaction respectively. As a safety evaluation factor, potential peak impact force and pushing force are selected, and velocity, force, and failure avoidance ability are selected for a dexterity evaluation factor. All of those factors are quantified by evaluation equations proposed newly or previously, and normalized in order to evaluate them together. By using the *SD* index, we actually evaluated the safety and dexterity of the 2-link manipulator which was assumed to execute a task, and depicted them on a space called as *SD* space. From the results, it was confirmed that the *SD* index could evaluate the safety and dexterity of a manipulator simultaneously and helped to grasp them easily. By using the *SD* index in design and control of a manipulator, it is expected that high safety and dexterity can be achieved simultaneously.

Chapter 6 Conclusion

In this research, we aimed at developing the manipulator system which can achieve high safety and dexterity in physical service processes by dealing with them not separately but simultaneously. To achieve the goal, three approaches has been studied, first, the proposal of the system that possess a high potential to realize them, secondly, the proposal of the control method that improves them with a consideration of interference between them, thirdly, the proposal of an index for evaluating them simultaneously. We have proposed the SSMs, *SD* control(*SD* torque limit, *SD* brake), and *SD* index corresponding to the system, control, and index respectively. Those are novel solutions dealing with safety and dexterity simultaneously, which have nearly not been studied to date. By this research, it is expected that the new approach simultaneously dealing with safety and dexterity is established, which is indispensable for a manipulator aimed at physical services.

論文審査結果の要旨

生活支援ロボットが今後十年間で急速に普及すると予測されている。そのようなロボットにおいて、安全性と器用さの両立は極めて重要な技術課題である。

本論文は、屋内環境において人間に物理的なサービスを提供する人間共存型サービスマニピュレータを対象とし、その安全性と器用さを同時に高い水準に両立できるシステム設計、制御、評価に関する提案を行い、その有効性を論じるものであり、全編7章からなる。

第1章は序論で、ここで対象としているシステムの安全性と器用さを考察、定義を行い、それに基づいてマニピュレータの安全性や器用さを扱った従来研究における課題を述べている。ここでは、安全とは、残留衝撃力と押し付け力が許容できるレベルであること、器用さとは、発生できる速度、力、および、失敗回避能力である、と定義している。また、これまでは安全性と器用さが独立に扱われてきているが、人間の実環境に導入する際には両特性を同時に扱うことが重要であることを指摘している。

第2章では、マニピュレータが安全性と器用さを同時に実現するための条件を述べ、その条件を満たすシステムとして、Safety Service Manipulator system(SSMs)を提案している。受動的・能動的な安全対策と器用さの実現方策が互いに大きく干渉することなく、両者が調和的に同時実現できるシステム設計が重要である。具体的な方法論として、Base Redundant Mechanism, Air Pressure Collision detection System, Controllable Torque limiter in Base(CTLB), Base redundancyを提案し、それぞれの概要と有効性について論じている。

第3章では、押し付け力の低減を目的とし、CTLBのようなトルクリミッタを採用した場合に生じる実行力の制限問題の解決法と、SSMsのダイナミックスを利用してCTLBの制限トルクを決定するSafety-Dexterity(SD)トルクリミット法を提案し、実験とシミュレーションを通してその有効性を確認している。

第4章では、衝撃力の低減率と実行速度の改善のために、マニピュレータと人間との衝突の際、安全かつ素早くマニピュレータを停止することができるSDブレーキ法を提案している。SDブレーキ法として、運動学的観点からのClosest Null space Vector Brake(CNVB)法と動力的観点からのDynamic Acceleration Polytope Brake(DAPB)法を提案し、それぞれの実現方法について詳述している。CNVBは現在の速度コンフィグレーションから一番近い零空間の速度コンフィグレーションに移動することにより、また、DAPBは最大実現加速度を表す加速度多角形の境界線上の加速度値を用いることによって、従来の全ての関節を停止させるブレーキ法より素早く、また、衝突方向を保ったままマニピュレータの衝突点を停止させることができる。

第5章では、マニピュレータの安全性と器用さを同時かつ定量的に評価できる指標であるSD indexを提案している。ここでは特に、マニピュレータの設計や制御、軌道計画の過程で安全性の確保と器用さの最適化を実現することを目的として、安全性と器用さの定量化と正規化の手法について論じている。

第6章と第7章では、結論、および、今後の課題を述べている。

以上、本論文は、人間に物理的なサービスを提供するマニピュレータにおける安全性と器用さの両立の問題に対して、ロボットの設計、制御、および、評価の観点からそれに対する解を提示したものである。この成果は、特に今後予測されるサービスマニピュレータの実環境への導入に重要な役割を果たしうだけでなく、情報科学の発展に寄与するところが少なくないと判断する。

よって、本論文は博士（情報科学）の学位論文として合格と認める。